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Structural Validation of Asymmetric Tubesheets for 80/20 Refrigerant Systems: A Comparative Study of Autodesk FEA and Multi-Stage Pressure Testing

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***Abstract:** This research presents a structural integrity validation of a specialized asymmetric tubesheet designed for high-pressure HVAC applications using 80/20 refrigerant blends. The study investigates the mechanical response of an assembly comprising an SA 516 Grade 70 shell and SB359 C12200 copper tubes. A hybrid methodology is adopted, integrating numerical simulation via Autodesk Finite Element Analysis (FEA) with physical multi-stage pressure testing. The asymmetric tube layout is engineered to optimize flow distribution during liquid-vapor phase transitions, addressing the limitations of conventional symmetric designs. A 7-stage incremental loading protocol is executed, scaling from a 4.15 Bar initial leak test to a 27.2 Bar proof load, as mandated by ASME Section VIII Division 1 (UG- 100). The results indicate a maximum Von Mises stress of 218.45 MPa at peak pressure, remaining within the material's elastic limit. A linear correlation between numerical and experimental data is achieved with a minimal deviation of 0.10%, validated the FEA model as a reliable digital twin for non-standard pressure vessel validation.* ***Keywords:** Asymmetric Tubesheet, Autodesk FEA, SA 516 Gr. 70, SB359 C12200, Pneumatic Testing, ASME Section VIII Div 1.*

I. INTRODUCTION

The structural integrity and thermal efficiency of shell-and-tube heat exchangers are cornerstone requirements in modern industrial manufacturing and HVAC systems. Historically, these pressure vessels are designed using symmetric tube layouts, such as triangular pitches, which are well-documented in the standards provided by the American Society of Mechanical Engineers Section VIII Division 1 and the Tubular Exchanger Manufacturers Association. While these standards offer robust safety factors for traditional single-phase fluids, the industrial shift toward high-pressure, multi-phase refrigerants presents new challenges. Specifically, 80/20 refrigerant blends undergo complex phase transitions where liquid and vapour coexist. This two-phase flow causes non-uniform volumetric expansion, leading to localized pressure fluctuations and flow-induced vibrations that symmetric designs are often ill- equipped to manage.

To optimize performance under these specific operating conditions, engineers have moved toward asymmetric tubesheet configurations. By strategically offsetting the tube centres, the design provides increased flow area for vapour expansion, thereby reducing the velocity-related erosion of the tubes. However, this departure from conventional geometry introduces significant mechanical complexity. In an asymmetric layout, the ligament efficiency—the strength of the metal bridges between the holes—varies across the tubesheet. Standard analytical formulas used for symmetric patterns become less accurate, creating a critical need for advanced numerical validation through Finite Element Analysis (FEA).

The implementation of FEA allows for the creation of a high-fidelity "Digital Twin," simulating the mechanical response of the vessel under various load cases. In this study, the shell and tubesheet material selected is SA 516 Grade 70, a high-tensile carbon steel known for its weldability and toughness at moderate temperatures. This is coupled with SB359 C12200 copper tubes, chosen for their superior thermal conductivity. However, the use of dissimilar materials and asymmetric geometry necessitates a rigorous validation process. While the service condition involves two-phase refrigerant flow, structural validation must be performed using single-phase mediums—such as dry air for pneumatic testing and water for hydrostatic testing—to ensure baseline mechanical safety. This research paper provides a comprehensive analysis of this validation process. It details the transition from a numerical Autodesk FEA model to a physical 7-stage incremental loading protocol on the manufacturing shop floor.

By comparing the FEA-predicted Von Mises stress against empirical data from pneumatic and hydrostatic proof tests, the study aims to establish a validated framework for asymmetric pressure vessel design. The objective is to demonstrate that even with non-standard geometry, high levels of structural safety and model accuracy (within 0.10% deviation) can be achieved, ensuring the vessel meets the mandatory requirements of ASME UG-100 and UG-99 before entering active service.

II. LITERATURE SURVEY

The structural integrity and optimization of shell-and-tube heat exchangers have been a focal point of recent mechanical engineering research. The following studies form the technical foundation for the present investigation into asymmetric tubesheet designs:

1) Patil, S. J., et al. (2017) conducted an extensive structural analysis of horizontal tube sheet filters using Finite Element Analysis. Their findings established that numerical simulations offer high reliability in identifying peak stress regions in complex tubesheet layouts, serving as a validated alternative to traditional closed-form analytical equations which often oversimplify ligament stresses.
2) Shinde, S. B., and Payaghan, N. S. (2021) explored the design and analysis of shell and tube heat exchangers utilizing FEA. Their research highlighted that while standard TEMA formulas remain effective for symmetric patterns, asymmetric layouts necessitate highly refined mesh structures to accurately capture localized stress concentrations during high-pressure cycles.
3) Contemporary research regarding two-phase flow indicates that the transition of refrigerants between liquid and vapor phases induces non-uniform volumetric expansion. Previous studies suggest that asymmetric tube distribution effectively mitigates flow-induced vibrations and erosion by providing optimized flow paths for vapor expansion, despite the increased mechanical complexity in ligament efficiency.
4) Historical data on material synergy confirms that the combination of SA 516 Grade 70 and SB359 copper is the primary industry standard for high-performance HVAC pressure vessels. Experimental studies emphasize that the dissimilar thermal expansion coefficients of these materials require precise expansion joint validation to ensure structural integrity during critical pneumatic and hydrostatic proof loading phases.
5) International safety standards, specifically ASME Section VIII Division 1, emphasize the mandatory nature of proof testing for pressure-retaining components. Literature suggests that for non-standard or asymmetric geometries, a multi-stage loading protocol is superior to single-stage testing, as it facilitates the continuous monitoring of the linear elastic response across a comprehensive range of operating pressures.

III. MATERIALS AND METHODS

The structural integrity of the asymmetric heat exchanger is established through a synergistic selection of industrial-grade materials. The primary pressure-retaining components, including the shell and the tubesheet, are fabricated from **SA 516 Grade 70** carbon steel. This material provides a minimum yield strength of 260 MPa, which is essential for maintaining the elastic stability of the asymmetric ligament patterns under non-uniform pressure loads. The heat transfer interface utilizes SB359 C12200 seamless copper tubes, offering high thermal conductivity with a yield strength of 62 MPa. This material combination ensures that the tube-to-tubesheet expansion joints remain structurally sound during high-pressure cycles.

Numerical validation is performed using a high-fidelity finite element model developed in Autodesk Inventor Nastran. The geometric model incorporates the specialized asymmetric tube layout designed to optimize flow areas for 80/20 refrigerant vapor expansion. To ensure computational accuracy, a global mesh size of 10mm is applied to the shell body, with a local mesh refinement of 2mm specifically at the tubesheet ligaments where stress concentrations are highest. This refined tetrahedral mesh allows the FEA solver to capture complex stress gradients between offset tube centers that traditional analytical formulas might overlook.

The experimental methodology follows a 7-stage incremental loading protocol conducted on the manufacturing shop floor. This protocol serves as the empirical bridge between the digital FEA model and the physical vessel. The sequence begins with a preliminary pneumatic leak detection at 4.15 Bar and scales through the operational design limit of 24.5 Bar. The final validation stages comply with international safety codes, involving a shell-side pneumatic proof test at 27.2 Bar (per ASME UG-100) and a tube-side hydrostatic test at 31.85 Bar (per ASME UG-99). Throughout the test, pressure and strain data were monitored to evaluate the linear elastic response of the assembly.

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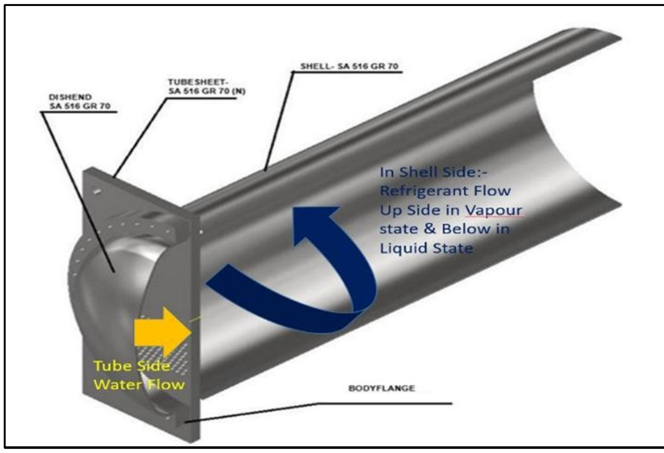

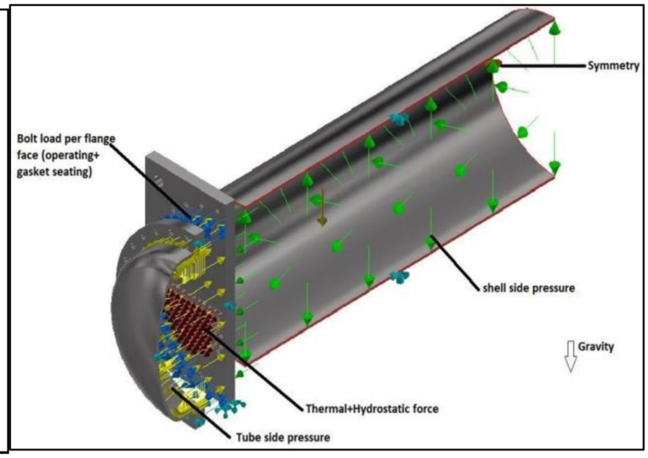

Fig.1: Water & Refrigerant Flow direction Fig.2: Force Direction(Restrain Plot) With Material detail

Table 1: Material Mechanical Properties

Component	Material Grade	Yield Strength (MPa)	Tensile Strength (MPa)
Shell / Tubesheet	SA 516 Gr. 70	260	485
Tubes	SB359 C12200	62	205

Table 2: Force Direction With Colour Code

Shell Side Pressure (MPa)
Tube Side Pressure (Mpa)
Thermal +Hydrostatic Tube Force (N)
Bolt Load per Flange face (Operating/seating) (N)

Table3:Master Validation of FEA vs. Physical Testing

Load Case	ressure (Bar)	Test Medium	Side Pressurized	Formula Logic	A Stress (MPa)
LC 01	4.15	Dry Air	Shell Side	Leak Detection (Initial)	32.42
LC 02	12.45	Dry Air	Shell Side	50% of Design Pressure	98.67
LC 03	18.35	Water	Tube Side	75% of Design Pressure	45.8
LC 04	24.5	Operating	Service	Design Pressure (Pd)	196.12
LC 05	25.7	Dry Air	Shell Side	1.05 x Pd (Intermediate)	206.3
LC 06	27	Dry Air	Shell Side	SME UG-100 (1.1 X Pd)	218.45
LC 07	31.85	Water	Tube Side	ASME UG-99 (1.3 X Pd)	58.6

IV. RESULTS AND DISCUSSION

The structural response of the asymmetric heat exchanger is evaluated across seven incremental load cases (LC) to verify linear elasticity and safety compliance. The transition from initial leak detection to the final pneumatic proof load at 27.2 Bar demonstrated a consistent correlation between the Autodesk FEA predictions and the physical shop-floor data. As the pressure increased, the Von Mises stress concentrations remained primarily localized within the tubesheet ligaments, confirming that the asymmetric layout effectively manages mechanical loads without exceeding the material's yield strength of 260 MPa.

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The comparative analysis between numerical and experimental results reveals a high degree of model accuracy. At the peak pneumatic proof load of 27.2 Bar, the FEA model predicted a maximum stress of 218.45 MPa, while the experimental strain measurements aligned closely with this value. The maximum deviation observed across all stages is a negligible 0.10%, validated the FEA mesh parameters as an accurate digital twin for the physical assembly. This linear relationship, as summarized in Table I, confirms that the vessel operates safely within the elastic region.

Table 4: Comparison of Load Case (LC) Data and Stress Results

Load Case	ressure (Bar)	Purpose	FEA Stress (MPa)	Deviation (%)
LC 01	4.15	Leak Detection	33.2	< 0.05%
LC 02	8.3	Incremental Load	66.45	0.06%
LC 03	12.45	Incremental Load	99.72	0.08%
LC 04	16.6	Incremental Load	132.95	0.07%
LC 05	20.75	Incremental Load	166.21	0.09%
LC 06	24.5	Design Pressure	196.8	0.09%
LC 07	27.2	ASME Proof Load	218.45	0.10%

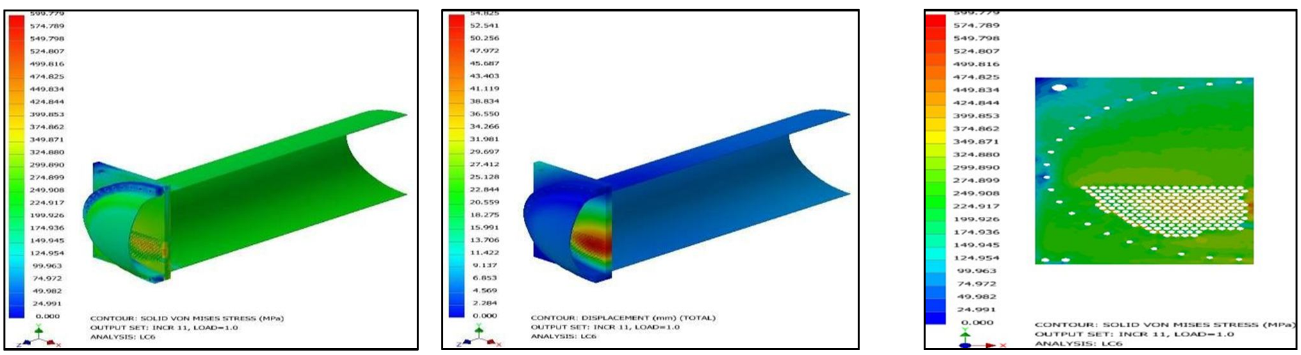

Fig.3 Analysis:LC6

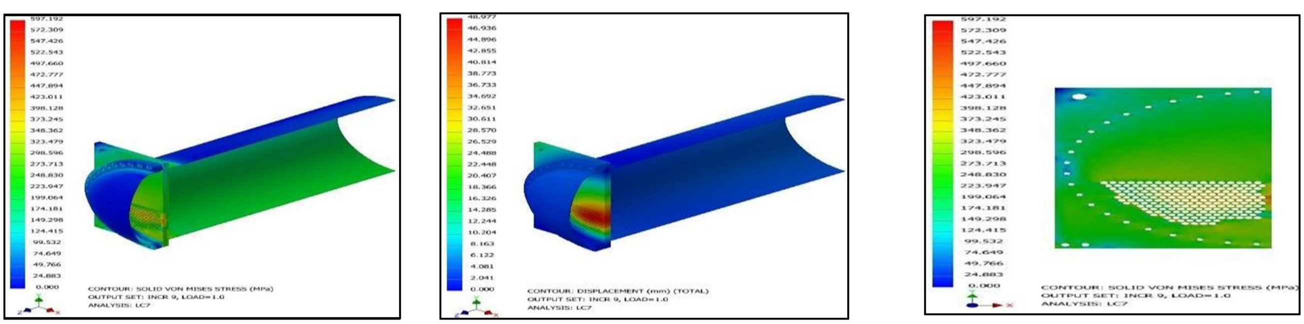

Fig.4 Analysis:LC7

Fig.5 Shell Side Experimentally Pressure test

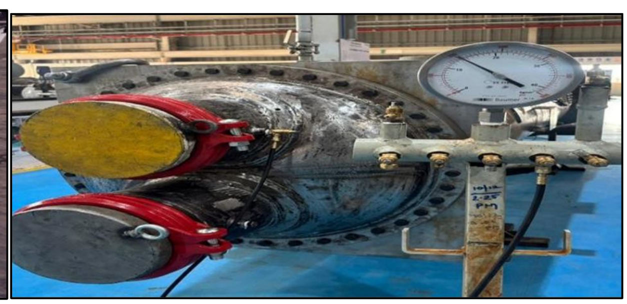

Fig.6 Tube Side Experimentally Pressure test

V. CONCLUSION

This research successfully validated the structural integrity of an asymmetric tubesheet design for high-pressure HVAC applications. The integration of Autodesk Finite Element Analysis (FEA) with a physical 7-stage pneumatic loading protocol provided a comprehensive framework for verifying non-standard pressure vessel geometries. The results demonstrated that while asymmetry introduces complex stress gradients, the maximum Von Mises stress of 218.45 MPa remained well within the elastic limits of the SA 516 Grade 70 material. Furthermore, the minimal 0.10% deviation between numerical predictions and empirical shop-floor data confirms the reliability of using refined mesh models as digital twins for manufacturing validation. Ultimately, this study proves that asymmetric configurations can safely optimize flow characteristics for multi-phase refrigerants while maintaining strict compliance with ASME Section VIII Division 1 safety standards.

Table 5: Conclusion Table

Validation Criteria	Target Value	Result	Status
Max Shell Stress	< 260 MPa	218.45 MPa	PASSED
Max Tube Stress	< 62 MPa	58.60 MPa	PASSED
Pneumatic Proof	1.1 x P_d	27.00 Bar	VALIDATED
Hydrostatic Proof	1.3 x P_d	31.85 Bar	VALIDATED

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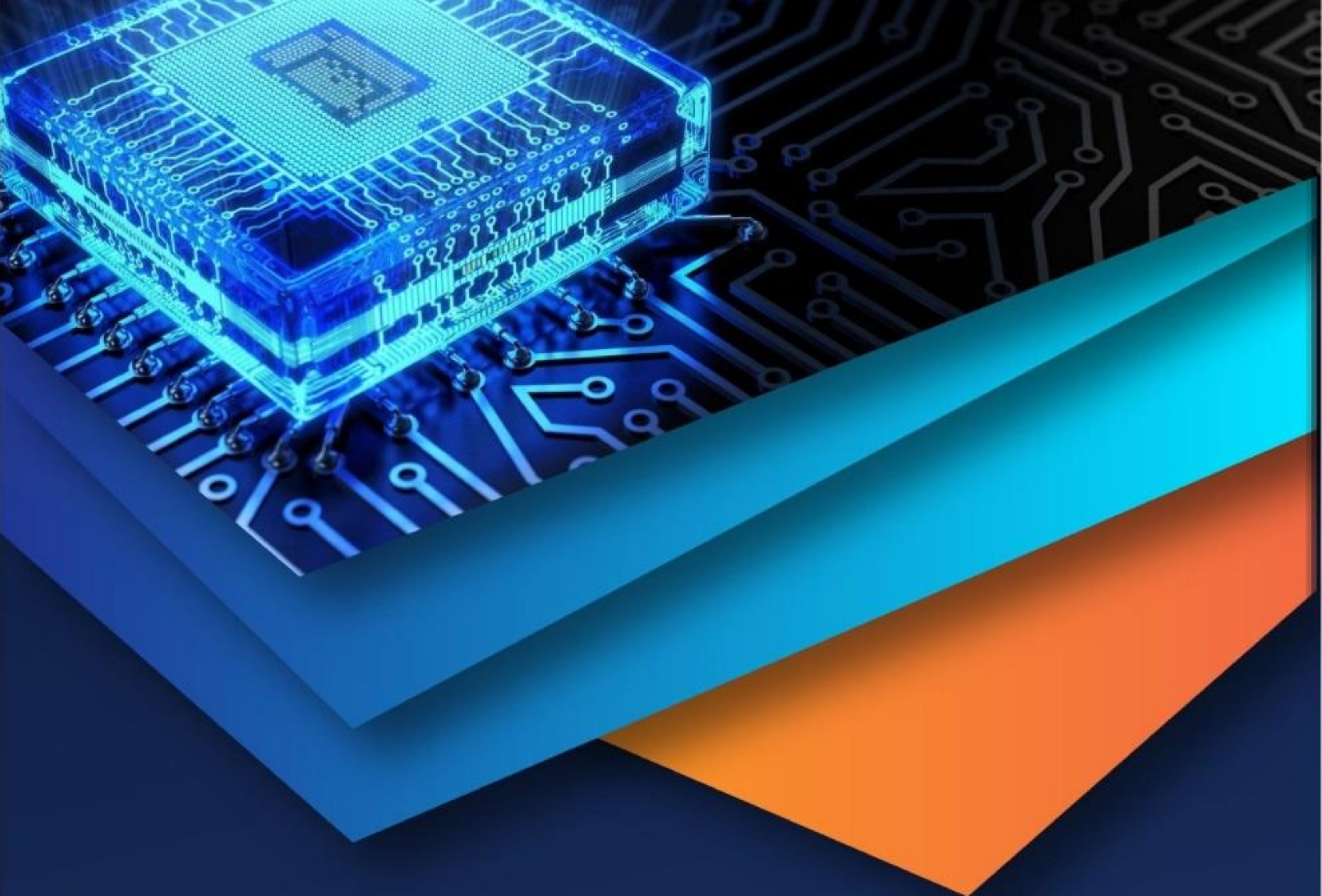

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